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HYDRAULIC PRESSURE IN CONCRETE

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POWER DIVISION

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HYDRAULIC PRESSURE IN CONCRETE

T.C. Powers[1]

The final report of the Subcommittee on Uplift in Masonry Dams of the Committee on Dams(1) states that: "The data applicable to the question of foundation uplift are held to be adequate to warrant a report on this phase. There are numerous unanswered questions and a scarcity of field data as to uplift effects in the concrete of the dam structure, and prospects for obtaining such information in the near future are not very promising. Hence, this report is presented as a statement of foundation uplift." The committee's avoidance of conclusions pertaining to pore pressure in concrete becomes understandable when one examines the various discussions of Mr. L.F. Harza's paper.(2)

During the past 15 years, work in the laboratories of the Portland Cement Association produced information concerning the structure of hardened portland cement paste having a direct bearing on the question of hydraulic uplift in concrete. In this paper I shall summarize that information.

This discussion will be restricted to a consideration of hydraulic pressure in the pores of concrete; it does not deal specifically with conditions in the foundation or at the junction of the dam and foundation.

Hardened cement paste in a modern concrete dam constitutes 15 to 20 per cent of the volume of concrete. Hardened paste is a continuous body extending from boundary to boundary of the structure. It envelops aggregate particles and air voids, isolating them individually. When water penetrates concrete, it penetrates the paste whether or not it penetrates aggregate particles. Hence, if the area factor for cement paste can be established, we will at least have found a lower limit for the area factor of the whole concrete.

Submicroscopic Structure of Hardened Paste

Hardened cement paste contains an amorphous material called cement gel. Within the boundaries of a body of paste, cement gel envelops the residue of unhydrated cement and non-gel part of the hydration products, principally crystals of calcium hydroxide. Gel may enclose also submicroscopic spaces—holes—representing residues of the original water-filled space in fresh paste that did not become filled with gel.

Cement gel is made up of granules so small that they fall in the class of sizes called colloidal. The smallness of these granules, together with the fact that they are bound together so as to form a porous solid, justifies calling the principal part of hydrated portland cement, cement gel.

The density of hardened cement paste depends upon the degree to which gel particles fill all available space. In the densest pastes that have so far been made, gel has the following physical characteristics:

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1) volumetric porosity, about 25 per cent
2) surface area of the gel particles, 6.0 million cm^2/cc of solid, or 14 million in^2/in^3, or 4,200 acres/cu.ft.
3) average specific gravity of the solids in the gel, about 2.44
4) diameter of the gel particles, about 100 Angstrom units, or four-tenths of a millionth of an inch.[2]

The surface area of gel particles, specific gravity, and volumetric porosity were measured experimentally.(3) The size of the average gel particle was calculated from specific surface of gel, on the assumption that gel is composed of equal spheres. Recently, electron photomicrographs were obtained showing that the particles actually are spheroidal and have an average diameter very close to that calculated from volume and surface area.

In cement paste of the kind found in mass concrete, the quantity of gel is insufficient to fill all space within the boundaries of hardened paste; some of the originally water-filled space remains unfilled. The porosity of paste as measured by its capacity for evaporable water usually ranges from 50 per cent upwards. We surmise that in such pastes, gel particles tend to be packed close together at sites of original cement grains,[3] and that unfilled spaces are residues of original interstitial space. In such pastes, gel is a three-dimensional network, webs of the net being made up of gel particles mostly in a close-pack arrangement.

Discussion of Area Factor

As has been brought out by Terzaghi and Leliavsky,(4) the area factor depends upon the nature of the ultimate particles. Ultimate particles are those parts of a porous, granular solid that water is unable to penetrate. In hardened cement paste, gel particles are the ultimate particles so far as hydrostatic effects are concerned; they present the surfaces with which water makes contact. At least two kinds of observation show that gel particles are the ultimate particles: (1) When water vapor is allowed to penetrate dry, hardened paste, some of it is adsorbed. After the amount adsorbed was measured the surface area of solids reached by water molecules was calculated.(3) From surface area, average size could be calculated, assuming equal spheres. The calculated average size agreed with the size revealed by the electron microscope, as already mentioned.(2) Direct measurements show that cement gel is permeable to water. Water flows through the exceedingly small interstitial spaces—we call them gel pores.

On the basis of information just summarized, the structure of concrete may be visualized as follows: every particle of aggregate and every air void in hardened concrete is embedded in a mass of exceedingly small spheroids. The spheroids average about a half millionth of an inch in diameter. They are packed together to various degrees, the maximum degree giving interstitial space of about 25 per cent. Water can penetrate the interstitial spaces among these particles and can transmit hydraulic force in a normal manner, so far as we know.

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2. This is a revision of an earlier published estimate of 140 A.
3. It should be understood that in the process of hydration the constituents of the original cement grains go into solution and that the new product, that which we have been discussing, is precipitated from solution. Only a small part of the original cement, a residue of the coarsest grains, survives if the conditions necessary for hydration are maintained long enough.

If gel particles in hardened paste were not attached to each other, that is, if they were only packed together as are particles in a bed of sand, the entire surface of each particle could be wetted. However, the ultimate particles in hardened cement paste are not discrete. They are connected to each other by bonded regions that water cannot penetrate. If gel particles were discrete, penetration of water into dry concrete would not merely cause a slight swelling, as it does, but it would also cause the gel to peptize. In other words, water would free gel particles from each other and the mass would lose its solidity. Water might even be able to disperse the material of which gel particles are composed, forming a true solution. Some gels can be readily destroyed by water as, for example, gels made of caustic alkali and silica, as found in concretes affected by the alkali-aggregate reaction.

Cement gel fails to peptize or dissolve because gel particles are linked by chemical bonds. The area thus bonded cannot be wetted and consequently cannot be subjected to hydraulic pressure.

Knowing something of the size and arrangement of gel particles we can estimate a possible area factor for cement gel when it is subjected to hydraulic pressure. Let us assume that particles are spherical and packed so as to have a porosity of 25 per cent. It is reasonable to assume further that the maximum number of points of contact is about 12 per particle. Therefore, each sphere might be bonded to its neighbors at 12 spots. A bond consists of a linkage between two atoms—a merging of force fields. The area of each spot can therefore be estimated from the radius of the bonded atom, data on atomic radii being available. With area per bond estimated, we need only to multiply by number of bonds per particle to find total bonded area per particle.

It works out that if each of the particles is bonded at 12 points by single pairs of atoms, 0.2 per cent of the particle area is bonded, leaving 99.8 per cent of the area accessible to water. Thus the wettable area fraction of gel particles might be very close to unity, but it would be definitely less than unity.

The foregoing discussion does no more than arrive at an estimate of a possible upper limit of the area factor. The actual area factor is obtainable only by experiment.

The latest values of area factors for concrete are those published recently by Serafim.[7] Following McHenry's[8] suggestion, Serafim estimated area factors (boundary porosity) by non-destructive tests, that is, by stress-strain measurements. Specimens were dried and then subjected to nitrogen pressure in such a way as to produce tension in the middle section of a cylinder by outflow through the ends. Some of the specimens were tested in the saturated state with water, as well as with nitrogen. Serafim's principal results are given in Table I.

Note that the factors obtained with nitrogen are like those obtained by Leliavsky and others in previous experiments; they range from .83 to .99 among the various grades of concrete. In some tests on specimens dried at 105° C, data not shown in Table I, factors not significantly different from unity were obtained. These results may have been influenced by internal cracks produced during drying.

Area factors obtained from water percolation are distinctly smaller than those obtained with nitrogen. The discrepancy between the two sets of results was explained by Serafim in terms of immobility (assumed) of adsorbed water molecules. This explanation, though possibly correct, seems doubtful on the basis of other considerations pertaining to the adsorbed state.

TABLE I.

Area Factors as Determined by Serafim

Ref. No.	Water-Cement Ratio by Weight	Area Factor as Measured With: Nitrogen	Water
3	0.72	0.90	--
8	0.72	.95	.74
1	0.68	.86	--
2	0.66	.86	--
4	0.60	.83	--
9	0.60	.89	.69
5	0.35	.85	--
10	0.35	.85	.42
11	0.35	.93	.44
7	0.30	.99*	--
12	0.30	.85	.43

* High value might be related to cracks produced during drying.

Both sets of data show that for water-cement ratios within the range practical for concrete dams, the area factor is a large fraction of the total area. With the possible exception of the three lowest values obtained with water, these factors obtained by Serafim seem compatible with what is now known about the structure of hardened portland cement paste.

Discussion of Intensity Factor

It is pertinent to inquire into conditions under which hydrostatic pressure can develop in the interior of concrete. For the most part the discussion will exclude considerations of seepage along construction planes, structural cracks, and other imperfections, though such seepage is obviously of practical importance. The purpose is to call attention to significant characteristics of concrete that do not seem to be generally known.

The same studies of physical properties of hardened cement paste already referred to account for the fact that concrete, especially mass concrete, is seldom if ever saturated at the time it goes into service and that in most of the structure it may never become saturated. In general, negative rather positive hydrostatic pressures prevail.

Since negative hydrostatic pressure may be an unfamiliar concept, the following remarks are offered to indicate what the term is intended to signify. In general, when we observe water flowing in any sort of conduit, we understand that flow occurs because of a difference in hydraulic pressure. Similarly, capillary rise indicates that a meniscus has produced a pressure difference, and if pressure at the base is called zero, pressure under the meniscus is negative. If capillary rise exceeds 33 ft. as it does in tall trees, the liquid actually is in tension.[4] When water is adsorbed by dry concrete, inward

4. An interesting short article on hydrostatic tension in liquids may be found in the Scientific Monthly, 58, 415, June 1949.

flow continues as long as hydrostatic pressure inside remains negative with respect to zero pressure outside. In this case, adsorption is due mostly to the spread of water over enormous internal surface areas (about 12,000 acres per cu. yd. of concrete) rather than to meniscuses, but the effect is the same.

The magnitude of negative pressure is an unsaturated region in concrete relative to zero pressure in a saturated region is a function of the degree of saturation of cement paste in the unsaturated region. It is a maximum when paste in the dry region is bone dry and zero when hardened paste is saturated. Thus, potential negative pressure are produced whenever pores in hardened paste become empty or partly empty. This is the usual condition. Even if concrete is sealed so that it can lose no water by evaporation, the chemical process of cement hydration reduces volume of water faster than solid volume increases and leaves originally water-filled space partly empty. This process has been called self-desiccation.(5)

The amount of water withdrawn from pores by self-desiccation is a function of degree of hydration of the cement. The amount of water withdrawn from pores is equal to about 28 per cent of the amount of water that becomes chemically combined. After a prolonged period of hydration, the amount of chemically combined water will be about 22 per cent of the weight of cement. Twenty-eight per cent of this is 6.2 per cent. Hence, for concrete containing 376 lb. of cement per cu. yd., the amount of water withdrawn from pores will be 0.062 x 376 = 23.3 lb. per cu. yd., or 2.8 gal. per cu. yd. of concrete. This is the amount of water that would have to be added to concrete to keep it saturated. Ordinarily, concrete does not receive anywhere near this amount from ordinary curing procedures. Moreover, it generally loses some water evaporation during construction. Hence, it is fair to estimate that within two or three months after concrete is made, each cubic yard of mass concrete will be short about three gallons of water for saturation. As long as this condition prevails, hydrostatic pressures in the interior of concrete are negative.

The period required for concrete in a dam to acquire water needed for saturation may be a very long time, as may be verified by computations based on measured permeability of mass concrete. In certain regions of a dam, specifically regions above tailwater level, a saturated condition may never be attained, except perhaps in the vicinity of leaky fill planes or structural cracks that serve as conduits.

Experiments described by Carlson and Davis(6) demonstrate the difficulty of producing positive pressures under conditions where evaporation can occur at the downstream face. In one of Carlson and Davis' experiments a 6-in. cylinder 96 inches long was exposed to hydrostatic pressure of 100 lb/in^2 at one end and to air maintained at 50 per cent relative humidity at the other. Arrangements were made to prevent water from passing the boundaries of the specimen except at ends. Bourdon gages were installed at various stations along the length of the specimen, one of them being only 4 in. from the upstream face.

In the early stages of the experiment small positive pressures were observed at stations closest to the upstream face. Within seven years every gage, including that 4 in. from the face, registered zero. The gages were incapable of registering negative pressures that must have existed.

The magnitude of negative pressure can be calculated by means of the relative humidity maintained by free water in concrete. Calculation involves the well known equation of Lord Kelvin that relates differences in free energy to differences in vapor pressure. It can be shown, for example, that if

humidity inside concrete at the exposed face is kept by evaporation at 50 per cent, hydrostatic pressure is about -14,000 lb/in². Hence, in the Carlson and Davis experiment if the downstream end of the test specimen was kept at that degree of dryness, hydrostatic pressure at the downstream end relative to pressure at the nearest point upstream where paste was saturated would be about -14,000 lb/in². Between the point where the concrete is just saturated and the upstream face, pressure would be positive, rising from zero to 100 lb/in² on a straight-line gradient. Therefore, total pressure drop from the upstream to downstream face would be about

$$100 - (-14{,}000) = 14{,}100 \text{ lb/in}^2.$$

Computation on a simplified basis indicates that with 100 lb/in² positive pressure on the upstream face the pressure would drop to zero at a point downstream only 0.7 in. from the face. The fact that a gage 4 in. away from the face registered zero, indicating either zero or negative pressure, shows that this computation was not far wrong. If the experiment had continued long enough to establish a steady state, rate of flow through the specimen would have remained practically unchanged if pressure at the upstream face had been reduced to zero, merely keeping the upstream face wet.

Because of development of negative pressure when concrete is subject to drying, we should expect negative internal pressures in a concrete dam in all parts where the downstream face is dry all or most of the time. At points below tailwater level, however, where evaporation from the downstream face cannot occur, development of positive hydrostatic pressure is only a matter of time[5].

Since the concrete above tailwater level tends to remain or to become dry by the process just described, water in concrete below tailwater level will in time be driven upward under the combined effect of positive pressure in the lower part and negative pressure in the upper part. However, as indicated by the Carlson and Davis experiment, positive pressure is likely to play only a small part in determining the final result, which means that positive pressures cannot be developed very far above tailwater level or away from the front face.

Hence, in an ideal, flawless concrete dam, we should expect a long period of slow change in moisture distribution, the period probably extending over many years. Finally, a practically steady state should be reached wherein positive pressures in concrete are found near the upstream face and near the tailwater level. In the rest of the structure, concrete should remain unsaturated and hydrostatic pressures should be negative. Variations from the pattern for a flawless structure will, of course, be produced by cracks, leaky fill planes, or perhaps by operation of spillways.

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5. It is doubtless unnecessary to call attention to the fact that negative pressures in the water films are fully balanced within the structure and therefore do not contribute to uplift forces produced in regions where the hydrostatic pressure is positive.

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c. Discussion of several papers, grouped by Divisions.

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